FACT SHEET NANO PRODUCTS

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Umwelt Bundes Amt
Für Mensch und Umwelt

Nanotechnology-based lighting systems: organic light-emitting diode (OLED)

1 Description of the application

1.1 Products and purpose of using nanomaterials[1]

Artificial lighting by means of electrical light sources plays a crucial role in everyday life, both for interior as well as exterior lighting applications. It helps improve the safety, comfort and performance on roads, in the apartment and at work. According to the International Energy Agency, nearly 20 percent of conducted electricity worldwide is used for lighting purposes. In Germany, 15 percent of consumed electricity is used for illumination. Lighting for commercial, trade and service applications accounts for the lion's share (UBA 2009). The demand for artificial light sources continues to rise, making the development of energy-conserving lighting solutions especially important.

Lighting has a major potential when it comes to the conservation of resources and climate protection. The so-called solid-state emitters are promising in this regard. They help drastically increase the energy efficiency of lighting. Aside from organic light-emitting diodes (OLEDs), the development of novel, nanotechnology-based lighting technologies likewise includes OLEDs combined with quantum dots, quantum dot-enhanced ILEDs[2] or silicon-based ILEDs (SiLEDs). Which of these lighting technologies will be playing a significant role in the future, and especially what kinds of impacts they will have on the environment, remains to be seen.

The fact sheet at hand is focusing on the uses of OLEDs for lighting purposes. Their function is based on nanotechnology-structured organic semiconductor materials. According to experts, this novel lighting technology will revolutionise both interior and exterior lighting as well as the display area (TVs, monitors, telephones) in the near future and in part replace existing systems.

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[1] Nanotechnology is the utilisation of engineered nanomaterials. Nanomaterials consist of definable, structural components with a size range of 1-100 nanometres (1nm = 10^{-9} m) in at least one dimension (see also recommendation of the Commission of 18 October 2011 with regard to the definition of nanomaterials (2011/696/EU). Nanoparticles are a subset of nanomaterials with a size range mentioned above in all three dimensions. Both natural as well as anthropogenic nanomaterials occur in the environment.

[2] ILED: inorganic light-emitting diode

OLEDs are large-area light sources[3], offering new design options with respect to lighting, such as large-area illumination of rooms, flexible luminous foils, flexible monitors or transparent light sources (BMBF 2012). They are particularly suitable for monitors (e.g., TVs, computer screens, monitors) and displays (e.g., for mobile phones and digital cameras). As such, they are already widely used on the market. In contrast to conventional technologies, their advantage is that the organic semiconductor material at the same time acts as image emitter and light source, achieving better energy efficiency and high resolution. The light emitted by OLEDs contains neither infrared nor UV radiation, making it especially suitable for sensitive areas, such as museums. OLED lighting products have been available on the market since 2010. OLED lighting systems might partly replace conventional systems within the next few years and decades and pave the way for completely new applications.

However, it is too soon to predict the development of OLEDs for lighting on the market, because relatively few and expensive OLED lighting products designed for a wide range of applications are currently available for purchase. As the OLED technology matures, the production volume will increase and the costs for OLED panels and lighting decrease considerably (US DOE 2011).

1.2 Function and structure of an OLED and nanomaterials it contains

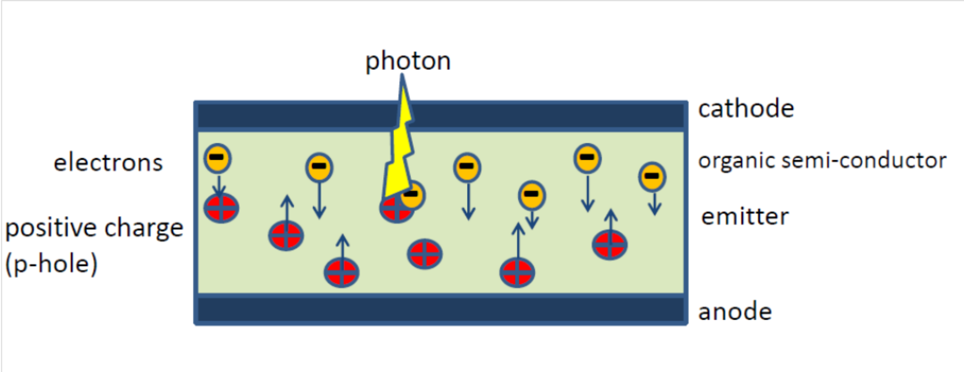
An OLED is a thin, flat luminous component with a thickness of usually less than 1 micrometre (µm[4]). It consists of at least one light-emitting layer (emitter layer) made of organic semiconductor material, is generally built with several layers, each with a thickness of up to 100 nanometres (nm [5]), which are positioned between two electrodes (see Figure 1). One or both electrodes of the OLED are transparent such that light can radiate toward one or both directions and gives it a translucent appearance when switched of. Compared to ILEDs, OLEDs have the advantage that the colour of the light can be customised to reflect the entire visible spectrum.

[3] The light source is a homogeneous luminous surface. OLEDs consist of several semi-conductive organic layers (Figure 1) and emit the light through the surface of these layers.

[4] 1 µm = 0.001 mm (millimetre)

[5] 1 nm = 0.001 µm

Figure 1: Schematic representation of the structure of an OLED



When switched on, voltage builds up between the electrodes which leads to a drift of the positive charge (p-holes) and the negative charge (electrons) in the semi-conductor layers toward each other. The charges accumulate in the emitter layer, creating an excited state when hitting each other: the exciton. Depending on the mechanism, this may be the direct excitation of a dyestuff molecule; or the dyestuff is excited by the energy released when the exciton decays. When the excited state of the dyestuff changes back to the basic state, a light particle (photon) with a defined wavelength is emitted. Two types of OLEDs are distinguished: the emitter layer consists of polymers (PLED) or of small organic molecules (small molecular organic LED = SMOLED).

Table 1: Materials used for OLED lighting (according to Spengler et al.)

Component	**Material**
Organic semi-conductor/emitter layer	Polymers (e.g. poly-p-phenylene vinylene, PPV) or molecules (light emission); triarylamines, triphenylene derivatives, copper phthalocyanine (hole conductor); tris(8-oxyquinoline) aluminium complex (electron conductor); partly contained: rare earth elements (e.g. europium), precious metals (platinum, iridium)
Cathode	Metal, e.g.: aluminium, barium, magnesium, calcium, ruthenium, silver alloys, lithium fluoride
Anode	Transparent conductive oxides (TCOs), mainly Indium Tin Oxide (ITO); alternatives: doped tin oxides, silver nanowire
Other layers, including electron injection layer, hole conducting layer	Lithium fluoride, caesium fluoride or silver; PEDOT/PSS (poly(3,4-ethylene dioxythiophene/ polystyrene sulfonate, copper phthalocyanine)
Carrier material/cover	Silicon, glass (e.g. borosilicate glass or normal soda-lime glass), polymer foil, metal foil (aluminium, stainless steel), flexible plastic
Housing/holder/frame	No detailed information / many possibilities
Electronic components	No detailed information

1.3 Relevant physicochemical properties of OLEDs

Table 2: Photometric capacities

Luminous flux (lumen, lm): light sources emit radiation within a defined spectrum. The radiant power described with the unit watt captures this emitted radiation indiscriminately across the entire light spectrum. However, the sensitivity of the eye varies for the different wavelengths. Taking into account this effect results in the luminous flux, also known as luminous power,

described with the unit lumen (lm).

Luminous intensity (candela, cd): luminous flux within a defined solid angle. The luminous intensity rates the light emitted by a light source in a defined direction.

Illuminance E (lux, lx or lm/m^2): luminous flux cast onto a defined surface.

Luminance (candela per m^2, cd/m^2): luminous flux emitted by a surface in a defined direction. Luminance is the measure that describes what the human eye perceives as brightness of a surface.

Luminous efficacy (lamp efficacy, lumen per watt): efficiency of a light source, that is, the ratio between the benefit (emitted luminous flux) and expenditures (consumed electric power). The luminous efficacy describes how much light can be generated with the used electricity (principle of maximisation). However, the goal is generally to keep the required electricity as low as possible with a given luminous flux (principle of minimisation). Consequently, other parameters, such as e.g. the PLI number are preferable.

Colour

The colour of the light emitted by OLEDs is dependent on the used dyestuff molecules. By stacking several layers emitting different colours, it is essentially conceivable to create any colour including white. Stacking is possible, because the organic layers are virtually transparent in the visible region of the spectrum.

Operating life

The operating life of LEDs, ILEDs as well as OLEDs is commonly indicated as the time after which the luminous flux still retains a certain ratio of the starting value[6]. OLEDs age at different rates, depending on their colour[7]. When using different OLEDs simultaneously, such as for screens, this may result in colour shift over time, which can only be corrected to a limited degree by means of subsequent adjustment. The operating life of products in which OLEDs are used is considerably shorter with 5,000 to 15,000 hours compared with the one of individual OLEDs. However, 100,000 hours are considered possible for products. For example, the EU project OLLA[8] already demonstrated an operating life of over 10,000 hours for OLEDs with 50.7

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[6] The complete failure of individual lamps or modules is generally not taken into account. For other types of lamps, the operating life is determined differently: for incandescent and fluorescent lamps for household use, it is generally the time after which 50 percent of lamps are still in working order, whereby a reduction in luminous flux is irrelevant (so-called average operating life). For commercially used lamps, the operating life is often the time after which the luminous flux still retains a certain rate of its initial value and after which a defined rate of lamps is still in working order (so-called useful life). As a result, it is difficult to compare information about the operating life of LEDs with the one of other lamps. Moreover, the relevance of the usually extremely high values for LED lamps should be viewed critically. A reduction of the luminous flux to 50 percent of the initial value – that is, the lamp only shines half as bright as at the beginning – is likely unacceptable for most applications.

[7] With respect to the useful life for white light sources and monitors, the useful life of the blue component is the limiting factor. For example, 5,000 hours (with 1000 cd/m^2) and 12,000 hours (with 100 cd/m^2) are indicated for white light sources (as of 2011). In comparison, conventional incandescent lamps have an operating life of approximately 1,000 hours and fluorescent lamps 3,000 to 15,000 hours.

[8] OLLA = High brightness Organic Light Emitting Diodes for ICT & Lighting Applications

lm/W at 1,000 cd/m² (OLLA 2009). The follow-up project OLED100[9] is designed to achieve a value in excess of 100,000 hours.

The operating life is dependent on a variety of environmental factors such as temperature, humidity and oxygen. In a cool place, an OLED with a low initial luminance always lasts longer than an OLED operated at maximum luminance from the start without cooling. To protect it from external influences such as humidity and oxygen, the OLED component must be encapsulated. However, this currently makes the commercial use on a flexible material difficult, because it is too easy for oxygen and water from the air to pass through many flexible plastic substrates.

Luminous efficacy/energy efficiency

The electric efficiency of lighting technologies is hotly debated in public. Media reports about new "records" involving the luminous efficacy of LEDs, particularly ILEDs, arouse genuine interest. It would be unreasonable to compare the performance of OLEDs under laboratory conditions with the routine performance of conventional lamps. The LED technology, particularly the one of OLEDs, is still undergoing the transformation "from the laboratory to the suitability for everyday use". Yet, the possibilities of LED technology are promising and far from fully exploited. But only few OLED products are currently available and experience with their use is sparse. Consequently, reliable conclusions about the electrical efficiency of this technology in everyday use are not possible at the present time.

2 Environmental and health aspects

2.1 Environmental aspects associated with OLEDs

Organic light-emitting diodes made of semi-conductive materials are large-area light sources. Current information about the achievable energy efficiency of OLEDs is comparable to the one of inorganic LEDs (ILEDs). But these are usually laboratory values, which have yet to be achieved with the products available on the market. No relevant environmental life cycle assessment quantitatively examining the raw material and energy consumption as well as the greenhouse gas potential across the entire life of OLEDs is yet available. They would not only consider the advantages during the utilisation phase, but also the energy consumption associated with the manufacture, e.g. because of the required, energy-intense vacuum chambers and the release of organic materials associated with the vapour deposition when only a part is deposited on the OLED. In contrast to conventional liquid-crystal displays (LCDs), no backlighting is required for those containing OLEDs. As a result, they consume less energy, thus generating less waste heat and are thinner, lighter in weight and require fewer materials for the manufacture. A study concludes that the energy use and hence the CO_2 emission are reduced in connection with the manufacture and use of OLED displays (Steinfeldt et al. 2004).

Only very small specific quantities of a variety of materials are incorporated in OLEDs, including compounds of rare earth elements such as lanthanum, cerium and yttrium, precious

[9] OLED100.EU: Organic LED lighting in European dimensions. The project was funded with close to 20 million Euros during the 7th research framework program from 2009 to 2011.

metals such as silver, miscellaneous (semi)metals such as indium, magnesium and aluminium as well as high-performance plastic materials. Similar to when they are used in many other electronic applications, these metals inevitably dissipate and get lost over the lifecycle of OLEDs.

Indium Tin Oxide (ITO) is generally used in the transparent anodes, while precious metals such as platinum or iridium are commonly used in the emitter layer. With respect to supply aspects, these metals are considered as critical raw materials (Erdmann and Graedel 2011). This is compounded by the extremely high specific energy consumption associated with the primary extraction and smelting as well as the emission of harmful substances (e.g. heavy metals). The search is on for alternatives of these metals. For instance, research is being conducted into the manufacture of purely organic emitters (Schlaak 2012). But as always, promising substitution solutions go hand in hand with new environmental or supply-relevant concerns. According to experts, the development of alternative materials, especially for the substitution of ITO, is essential for the realisation of affordable OLED lighting (US DOE 2011, Spengler et al.), wherein the current price is not so much dictated by the indium content[10], but by the expensive ITO sputtering production processes[11].

A negative aspect in connection with the use of OLEDs is the expected dissipative, i.e., irreversible loss due to fine distribution in glass or plastic materials because of the extremely low concentration of used engineered metals. Even if significant quantities of OLEDs would be collected as waste by means of return and recycling systems, the recovery and required enrichment would be fairly unlikely from a technical point of view. A study investigating the recyclability of flexible plastic OLEDs has shown that only 0.07 to 3 percent of used metals were recovered (Barruetabena et al. 2011).

It is expected that OLEDs will be mass-produced in the future and that large quantities of OLEDs will be disposed of: according to an estimate, 10,000 tons of flexible OLEDs will be produced globally in the year 2022 alone (Colegrove 2009). It would therefore be appropriate to not only launch an investigation into the treatment of used OLEDs and their recycling, but to also provide substance flow management to ensure proper capture and treatment.

2.2 Ecotoxicity of materials contained in OLEDs

The materials used in OLEDs are not nanomaterials within the meaning of the EU commission definition, but nanostructured thin layers. Therefore, the evaluation of potential ecotoxicological effects does not refer to nanospecific effects, but to the used materials in general.

The components of the individual layers may vary depending on the manufacturing method. Therefore, the potential (eco-)toxicological effects cannot be assessed broadly, but only in consideration of the individual components of OLEDs. The available ecotoxicological knowledge is illustrated below to exemplify some of the used materials. Yet, especially the

[10] The module price of an ITO element only reflects a small percentage of the indium loads it contains.

[11] Sputtering is a special coating process that usually involves conductive materials.

different organic semi-conductors and anodes also contain materials whose (eco-)toxicological potential has yet to be studied in detail.

Conductive polymers are used in the organic semi-conductors, such as derivatives of poly(p-phenylene vinylene) (PPV). Like other plastic materials, polymers are considered uncritical from an ecotoxicological point of view, as they are relatively inert. No findings are available concerning the risk potential of additives, if any.

Depending on the composition, aluminium-tris(8-hydroxyquinoline) (Alq3), which is responsible for the colour, is used for example in the emitter layer. Data for Alq3 about the ecotoxicology as well as about the persistence, degradability and environmental mobility or about the potential to accumulate in environmental organisms are insufficient. Alq3 is considered non-combustible.

Data suggesting persistence in the environment are available for copper phthalocyanine (pigment blue), often used in the p-hole conducting layer. The substance does not bioaccumulate and there is no evidence of an ecotoxic effect (registration data pursuant to the REACH-EU regulation on chemicals).

Transparent conducting oxides such as Indium Tin Oxide (ITO) are used in the anode. While toxicology data are available, the effects on environmental organisms are unknown. Based on the projected growing use for the manufacture of transparent electrodes, a rising entry into the environment is anticipated. Ecotoxicology data should therefore be generated. As only limited quantities of indium are available and because it is extremely expensive, major efforts are underway to produce less cost-intensive transparent and conductive coatings. Some of the more economical alternatives of ITO include doped zinc oxides and silver nanowires. Both zinc oxide as well as silver is associated with harmful effects on aquatic organisms, even at low environmental concentrations. They are classified as substances hazardous to waters class 2 and 3, respectively.

However, the release of hazardous substances used in OLEDs in connection with their application is fairly unlikely, as they are encapsulated for protection against moisture and oxygen. The release and exposure of the environmental compartments during the utilisation phase is virtually impossible.

OLED-based lighting systems and display applications must be collected separately from municipal waste (see ElektroG (Electrical and Electronic Equipment Act)[12]). But the ElektroG does not contain any regulations with regard to the selective treatment of nano-structured materials, meaning that they might be released during the treatment. If improperly disposed with the tailings, OLEDs would be incinerated in waste incineration facilities with ultra-efficient emission control. If OLEDs are disposed other than by way of the intended disposal method according to ElektroG or with the tailings, there is a risk of environmental exposure caused by ageing and weathering processes.

A comprehensive assessment of the risks of OLEDs for the environment is currently impossible for lack of information about the individual used materials.

[12] Law governing the sale, return and environmentally sound disposal of electrical and electronic equipment (ElektroG)

2.3 Health-related aspects

OLEDs contain substances that are harmful to the health (e.g. triphenylenes). If the light sources are used as intended, the chemical substances contained in OLEDs are not released, because OLEDs are encapsulated to protect them against external influences. Whether the used substances seep into the environment after breakage, and may hence pose a risk to the health, should be examined. The fact is that the quantities used in the luminary are extremely small. Ultimately, it is the manufacturers' duty to conduct an evaluation prior to launching the product on the market.

The biological ("visual" and "nonvisual") effect of the realised lighting situation depends on the properties of the used lamp with respect to spectrum, irradiance, radiancy, spectral energy distribution (geometry) and chronological change during the exposure and is determined by the individual circumstances and processes.

In contrast to fluorescent lamps, OLEDs neither emit infrared nor ultraviolet (UV) radiation. Potential health risks caused by UV radiation are therefore not an issue, as long as this statement applies to all types of white light OLEDs. The assessment by the Commission on Radiological Protection based on comparable measurements arrives at the same conclusion (SSK 2010). The emission of infrared (IR) radiation of currently available white light OLEDs is negligible, and heat-related harmful effects are thus only possible with luminances that considerably exceed the maximum dazzle threshold. Nevertheless, we recommend incorporating the demand to limit the relative contribution of infrared radiation to the spectrum of white light OLEDs into the standards.

Researchers recommend studying the long-term risks and effects induced by underestimated or impaired regeneration and repair processes in persons of different ages and integrating them in the risk assessments (Spengler et al.).

3 Legal framework

In contrast to ILEDs, OLEDs aren´t covered by the EU requirements with regard to the ecodesign or energy consumption labelling[13]. As a result, product information requirements have yet to be formulated. However, in the future, they should be included in the range of application of the corresponding regulations relating to lamps.

OLEDs must comply with the provisions of the First Ordinance of the Product Safety Act[14], which contains provisions with regard to the quality of electrical equipment.

[13] The definitions contained in the directives no. 244/2009/EU (Commission regulation (EC) no. 244/2009 of 18 March 2009 implementing Directive 2005/32/EC of the European Parliament and of the Council with regard to ecodesign requirements for non-directional household lamps) and no. 1194/2012/EU (Commission regulation (EU) no. 1194/2012 of 12 December 2012 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for directional lamps, LED lamps and related equipment) as well as 874/2012/EU (Commission delegated regulation (EU) no. 874/2012 of 12 July 2012 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of electrical lamps and luminaires) are based on ILEDs. All three regulations contain product information requirements. They differ in the concerned lamp types and the content of the required information.

[14] 1. ProdSV – Ordinance on the provision of electrical equipment designed for use within certain voltage limits on the market.

Equipment containing OLEDs is considered electronic equipment within the meaning of the Directives 2002/96/EC and 2012/19/EU (WEEE[15]) as well as the Directives 2002/95/EC and 2011/65/EU (RoHS[16]). Consequently, manufacturers of equipment containing OLEDs are required to comply with the ban on substances pursuant to the ElektroStoffV[17] as well as with the registration, submission of quantity reports and the disposal of old equipment pursuant to the ElektroG[18]. Because of the diversity of possible uses of OLEDs, they may be excluded from the current ElektroG; a possible example is a combination with textiles (especially clothing). However, based on the currently (as of 1 February 2013) applicable definitions for lamps and luminaires[19], equipment containing OLEDs should always be deemed a lamp rather than a luminaire. Starting from 2018 at the latest, the WEEE Directive and the ElektroG provide an open range of applications, which is supposed to include all equipment containing OLEDs, irrespective of categories.

The Electrical and Electronic Equipment Act stipulates that OLED-based lighting systems and display applications must be collected separately from municipal waste (section 9, subsection 1 ElektroG). In its grounds for consideration (EEC 18), the WEEE Directive explains that an exposure to nanomaterials during the recycling is possible in connection with the waste disposal phase. To mitigate potential risks to the human health and the environment associated with the treatment of old electrical and electronic equipment containing nanomaterials, the Committee is asked to evaluate the need for special treatment (Article 8(4)).

The substances used for the manufacture of OLEDs within the EU are subject to the provisions set forth in the REACH regulation (EC) no. 1907/2006[20]. For OLEDS which are imported into the EU only the relatively lenient REACH obligations for articles apply.

4 Need for research and development

The following need for research and development has been identified with respect to the environmental behaviour of materials contained in OLEDs, their impacts on humans and the environment as well as the environmental sustainability of OLEDs:

- Evaluation of the significance of the resource consumption of rare raw materials;

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[15] WEEE Directive: Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 and Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE: Waste of Electrical and Electronic Equipment)

[16] RoHS Directive: Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 and the Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 concerning the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS: Restriction of Hazardous Substances)

[17] Ordinance on the restriction of the use of certain hazardous substances in electrical and electronic equipment (ElektroStoffV)

[18] Act governing the sale, return and environmentally sound disposal of electrical and electronic equipment (ElektroG)

[19] see http://www.stiftung-ear.de

[20] Regulation (EC) no. 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the registration, evaluation, authorization and restriction of chemicals (REACH)

- Examination of the behaviour of substances contained in OLEDS during disposal;
- Evaluation of the recycling options for the recovery of specific metal loads from OLEDs. Potential synergies for the capture and disposal of similar functionalised product groups such as organic and thin film photovoltaic modules or electrochromic glasses should also be studied in this context. The effects on the collection and disposal pursuant to the ElektroG must be reviewed;
- Increase of the energy efficiency and the operating life of OLEDs through optimisation of the lighting technology.

5 Conclusion

The Federal Environment Agency considers OLEDs to be an interesting factor in the future development of the lighting sector. Compared to conventional incandescent lamps, the energy requirement to generate a specific luminous efficiency is lower, while the operating life is at the same time considerably longer than the one of an incandescent lamp.

Compared to the widely used energy-saving lamps, OLEDs do not contain mercury, which might be released in case of breakage. The quantity of included hazardous substances is extraordinarily small due to the nano-coating and no health risk is therefore expected even in case of breakage. No release of nanoparticles in connection with the technology (coating) is expected.

Only relatively few lighting products containing OLEDs are currently on the market. Furthermore, they all have a different design. Based on the dynamic development of the innovative nanotechnology-based lighting technologies, it is difficult to predict which of these technologies will emerge to play a key role in the future.

The early evaluation of the environmental sustainability of new technologies is a main concern for the Federal Environment Agency. This applies in particular if nanomaterials come into direct contact with humans or reach the environment during their lifetime. However, this is not a concern in the case of OLEDs.

Questions about the significance for the consumption of resources as well as the possible recovery of the used materials remain unanswered. In this regard, only a limited amount of data concerning OLEDs is available. We therefore recommend further studies of this set of problems.

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